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Impacts of climate change on livestock and possible adaptations: a case study of the United Kingdom

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Impacts of climate change on livestock and possible adaptations: a case study of the United Kingdom

Abstract

Agriculture is a vital economic sector, providing food, fibre, and energy to a growing human population. Livestock are an important part of this sector, however the evidence and understanding of how a changing climate may affect livestock production systems, or how they may adapt to the changes, is a neglected area compared to the research into crop production. In this paper, we focus on livestock in the United Kingdom (UK), as an example of a temperate region likely to experience at least moderate changes in climate that will require changes to the way agricultural systems operate. We summarise the projected climate changes in this region, identify the main impacts likely to affect livestock agriculture, and discuss potential adaptation options at the farm level. We also categorise the adaptation options by the types of costs they incur, emphasising that many of these options involve management changes rather than investment and therefore no financial cost. Finally, we discuss the need for longer term planning to prepare for changes that have not yet been observed.

Introduction

Globally, agriculture is a vital economic sector, providing food, fibre, energy and livelihoods to a growing human population [HLP 2016]. It is however also particularly exposed to the impacts of climate change. For national governments and their agencies, understanding the ways in which agriculture can effectively adapt to the impacts of climate change is an important component of achieving sustained production, and an agricultural sector that is resilient to climate shocks and remains productive and competitive into the future.

The impacts from climate change will vary globally and some regions will experience more pronounced and rapid changes than others (IPCC, 2018). However, without adaptation even regions with relatively mild projected changes may experience production losses. With this in mind, we focus on the United Kingdom (UK) in this article, but the analysis will be important for a range of countries with similar production systems. The UK is in the cool temperate zone within which its climate is influenced by its geographical proximity to the Atlantic seaboard of continental Europe. Thus the UK typically experiences cool summers and mild winters with no strongly pronounced rainfall pattern, but with significant spatial and inter-annual variations. Livestock agriculture in the UK tends to be located in the cooler, wetter and more variable climates, often on heavier soils and more challenging topography that are unsuited for crops. These features can limit options for adaptation and change for farmers.

Agriculture in the UK faces a number of competing demands and drivers. Not only a producer of food, UK agriculture must fulfil other diverse demands including environmental protection, landscape provision, and rural livelihoods. Thus actions at the level of the individual agricultural enterprise may be subject to constraints at the level of European Union (EU) and domestic policy, as well as social constraints. Livestock products are of greater value to the UK than crops (GBPm 12,686 compared to GBPm 8,075 in 2016 (Defra et al. 2017) so a thorough analysis of the possible effects of climate change, as well as options available to adapt, is both justified and overdue.

Historically, research into climate change and agriculture focused on identifying and quantifying climate impacts with an emphasis on implications for crops (e.g. Lobell et al. 2011, Rosenzweig et al. 2014, Moriondo et al. 2010, Rial-Lovera et al. 2016). More research is now emerging into options for adaptation to these climate impacts (e.g. Iglesias et al. 2012, Hoving et al. 2014, Marshall et al. 2018; Rojas-Downing et al. 2017) but again, the literature on impacts and adaptations relating to crops dwarves that relating to livestock (Porter et al. 2014). This article bridges this gap by summarising the effects of climate change on the livestock sector and synthesising adaptation options.

Using the IPCC's current conceptual framework for climate risk (Cardona et al., 2012) as a basis for our analysis, we refer to climate impact as the effects of climate change on human and natural systems, in this context livestock systems, and risk as the potential negative impacts of climate change where something of value is at stake. In this framing, risk is identified as a function of the hazard (e.g. changes in precipitation, temperature, extremes), exposure, vulnerability and likelihood. We use the 'hazards' component of risk and climate impacts to identify the main climate impacts affecting livestock production in the UK and structure the paper around these impacts. We also include the possibility of opportunities as well as negative impacts arising from climate change for livestock agriculture in the UK.

Impacts and adaptations relevant and appropriate for the livestock sector in the UK are identified in this article both from existing literature and expert opinion, focusing on the private adaptations that individual farmers can undertake, rather than the sectoral, national level planning approaches that must be undertaken concurrently. Adaptation is very locally specific (Adger et al. 2005), and will depend on the local biophysical characteristics of the land, the type of farming system, and the aims and capacities of individual farmers and land managers. As such we do not provide recommendations for specific adaptations, but identify the types of costs that each type of adaptation incurs, with the aim of demonstrating that many adaptations can be made at low cost through changes in timing and management, often in the short term as changes are observed. This high-level cost assessment is designed to inform decision-makers and to contribute to adaptation planning at the farm level.

The primary aim of this paper is to fill a current gap in literature by synthesising the existing literature on climate impacts, adaptations and their costs to the UK livestock sector. The paper is aimed at a range of audiences, from researchers, extension agents and policy-makers needing to understand the types of adaptations available to farmers in the UK. The research audience includes those researchers investigating the biophysical aspects of impacts and adaptations; researchers interested in the social and economic aspects of adaptation in livestock; and researchers conducting participatory research in this general area, who would use this paper as a guide.

The rest of this paper is outlined as follows. In section 2 we briefly summarise the relevant climate projections for the UK, and in section 3 we identify the major impacts likely to affect livestock systems resulting from these changes in climate. Section 4 then identifies and discusses the main adaptation options available to farmers in addressing these impacts, and in section 5 we present a high-level analysis of the types of costs that each adaptation will incur. In section 6 we discuss the findings and the wider implications of climate change and adaptation for the livestock sector in the UK and conclude.

1. Climate projections for the UK

The most recent climate projections for the UK (UKCP18) are based on HadGEM3-GC3.05 and the models that informed the IPCC 5th assessment, resulting in probabilistic projections of climate change for certain key climate variables (Lowe et al. 2018). This allows an improved representation of some of the uncertainties involved. The longer term UKCP18 projections for RCP8.5 for the period 2080-2099 (at the 50% probability) suggest that summer temperatures will increase by between 2 deg C and by 5 deg C while winter temperature will increase by 2 deg C. The seasonal changes for precipitation (at the 50% probability) may be considerable by the end of the century, with decreases of potentially 60% in summer precipitation for parts of southern England and increases in winter precipitation of up to 30%,. These changes however do not show potential changes in extreme weather events, such as flooding, drought, heat waves, and heavy storms which are projected to increase (EEA 2017) and likely to cause more damage in the short and medium term than the longer term mean changes. We focus on the adaptations to these types of events in this paper.

Several studies have been carried out assessing the impact of past extreme weather events (particularly heat waves) on the agricultural sector in the UK and Europe (Ciais et al., 2005; COPA COGECA 2003., Subak, 1997; Hunt et al., 2006, Dunn et al. 2014; Fodor et al. 2018). These provide useful indicators of the types of events that might occur more frequently and intensely in the future, and the likely impacts if learning and change does not occur.

2. Climate impacts on UK livestock systems

The implications of the projected changes of climate on livestock production are likely to be both direct and indirect. The direct effects on livestock include impacts on animal health, welfare, growth and reproduction, while the indirect effects are due to the impact of climate change on the productivity of pastures, forage crops and feeds. A more complex indirect impact may result from the effects of climate change on the economic cost of inputs, e.g. feedstocks that are imported into UK systems from global markets. The identification and grouping of impacts in this paper was developed by the authors and is in line with the most relevant literature in this area (viz. Iglesias et al. 2012; Rojas-Downing et al. 2017).

Considerable research has been carried out on the primary effects on, and interactions of climate change with, plant growth and yield (e.g Moore and Lobell 2014, 2015). Much of this research is summarised in the 'Food security and food production systems' chapter of the Fifth Assessment

Report (AR5) of the IPCC (Porter et al. 2014). Iglesias et al (2012) assess climate impacts on agriculture for five agroclimatic areas of Europe, based on an extensive literature review. Less research has been carried out on the impacts of climate change on pastures and livestock specifically (e.g Höglind et al. 2013; Lee et al. 2013; Hill and Wall 2015; Lüscher et al.2014 ; Van laer et al. 2015, Fox et al. 2015; Mäkinen et al. 2015; Phelan et al, 2015 Rinaldi et al, 2015, Weindl et al. 2015; Schüller & Heuwieser, 2016).

The second UK Climate Change Risk Assessment (CCRA) published in 2017 (and to be updated every five years) identifies the climate impacts and the urgency of further actions to track current and future risks likely to affect UK agriculture over the coming century. Within the context of the natural environment, the key risks identified were those due to water scarcity and flooding, changes in the suitability of land for agriculture, increased risks of pests and pathogens with the risks exacerbated by extreme weather events (Brown et al., 2016). The report noted that many of the risks are interrelated and this must be taken into consideration when identifying adaptation responses. In terms of livestock production, there are interactions between the soil, climate and fodder that need to be considered. As well as risks, the 2017 CCRA pointed out that there will also be opportunities to diversify existing swards and to grow alternative forage crops.

During winter, the warming associated with climate change is likely to reduce purchased and preserved feed requirements, increase survival and lower energy costs (Maracchi et al., 2005). However, extreme cold and wet weather can have negative impacts on production (van laer et al. 2014). Similarly, warming in summer may result in heat stress, which can result in reductions in dry matter intake (O'Brien et al. 2010; Hill and Wall, 2017) and milk production (Hill and Wall, 2017), the fertility of cows and sows (Amundson 2006), and can also affect animal welfare (van laer et al. 2014). With respect to intensively housed systems, while the exposure of the housed livestock to the weather is more easily controlled (Nienaber & Hahn, 2007), extreme temperature events or long-term increases in temperature that are beyond the ventilation capacity are likely to result in increased energy and water use and an increased risk of disease (Skuce et al. 2013). Similarly, the risk of animal welfare and diseases issues will be increased when transporting live animals (Villarroel et al., 2011).

Climate change is projected to result in an increase in yield for temperate grasslands (Abdalla et al., 2010; Shrestha et al., 2015), although the length of the grazing period may decline for western Britain (Phelan et al., 2015). The impact on the seasonality of production is affected by complex interactions between the botanical composition of the sward and its cutting / grazing management (Bloor et al., 2010; Bloch et al., 2015) and the degree of warming and changes in precipitation (Fridley et al, 2016). In addition, increases in CO_2 and changes in climate may affect the digestibility of the sward (AbdElgawad et al, 2014; Lee et al, 2017; Dellar et al, 2018)) which will impact on the dry matter intake of the grazing animal and hence productivity. CCRA (Brown et al., 2016) highlights that there is a potential risk of poaching damage (the soil structure becoming damaged and soil becoming compacted); however, the study by Brown (2017) suggests that for Scotland the risk of poaching will decline in summer with climate change due to the warmer and drier summers.

In relation to the risk of diseases the seasonality of helminth parasites will change as a result of increased temperature, increased number of generations per year, and an increased risk of the parasite surviving over the winter period (Skuce et al., 2013, Fox et al., 2015). Although infection by helminths can cause death, they are more likely to reduce the productivity of the animal (Skuce et al., 2013). The increases in rainfall are resulting in increases in the prevalence of liver fluke, Fasciola hepatica, and hence the increased risk of disease in cattle and sheep. Nevertheless, the impact of climate change on prevalence of the parasite is dependent on the sensitivity of the particular parasite to the changes in temperature and rainfall experienced and extreme events, and the interplay of parasite with the management of the pasture and the livestock (Charlier et al., 2016; Verschave et al., 2016).

These key impacts for UK livestock are summarised in Table 1, drawing on other key literature identifying impacts of climate change on livestock (Iglesias et al., 2012; Rojas-Downing et al., 2017). We group these into five broad categories of climate impacts (heat stress; variable precipitation and climate extremes; increased likelihood of agricultural pests and diseases; changes in pasture area; and forage quality and quantity) which will be used to frame the identification of adaptation options in the following section.

Table 1 Potential impacts of climate change on UK livestock systems and the four broad categories of impacts they relate to (Heat stress; variable precipitation and climate extremes; pests and diseases; pasture area and forage quality and quantity changes).

Impacts identified in the literature	*Broad categories*
Increasing CO_2 levels resulting in changes in herbage growth and quality	Forage quality and quantity
Changes in temperature, rainfall, radiation and humidity	Pasture area; forage quality and quantity; pests and diseases; variable precipitation and extremes
Extreme events (e.g. heat waves, hail, drought and flooding)	Pasture area; heat stress; variable precipitation and extremes
Shifts in crop suitability	Pasture area; forage quality and quantity; variable precipitation and extremes
Changes in plant nutrition and increasing incidence of weeds, diseases and pests	Forage quality and quantity; pests and diseases
Degradation of resources (e.g. soil erosion)	Pasture area; variable precipitation and extremes
Increased flooding	Variable precipitation and extremes; pests and diseases
Increased risk of drought and water scarcity	Variable precipitation and extremes; pasture area; forage quality and quantity; pests and diseases
Deterioration of soil quality	Pasture area changes
Salt water intrusion in coastal agricultural areas	Pasture area changes
Increased risk of agricultural pests, diseases, weeds	Pests and diseases
Deterioration of livestock conditions - heat stress with implications for production, reproduction and health	Heat stress
Increase in optimal farming conditions	Discussed separately
Improvements in livestock productivity	Discussed separately

3. Identification of adaptation options

In this section, the main adaptation options to address the impacts identified previously are discussed, grouped into the four categories presented in Table 1.

3.2.1 Heat stress

More frequent and prolonged periods of higher temperatures resulting in potential heat stress could present production challenges, even in northern regions of the UK, including Scotland (Hill and Wall 2015), where there has thus far been little need to adapt to heat stress. Not only can heat stress cause distress and animal welfare problems, it can lead to reduced yield and fertility in animals, and in severe cases, mortality. Renaudeau et al. (2012) provide a summary of impacts of heat stress on livestock production as well as a review of evidence for many of the adaptations discussed below. All animals have a range of ambient environmental temperatures, known as the thermal neutral zone; temperatures beyond this range affect livestock negatively - sometimes with a delayed effect so that the impacts of summer heat stress may not appear until the autumn (Herbut et al. 2018). Heat stress starts at the upper critical temperature of this zone. In physical terms it implies that the animal cannot dissipate an adequate quantity of the heat to keep the body thermal balance (Hill and Wall, 2015). This effect is induced by changes in a combination of environmental factors (e.g., sunlight, thermal radiation, air temperature and humidity), animal properties (e.g., rate of metabolism and moisture loss) and thermoregulatory mechanisms such as conduction, radiation, convection and evaporation (St-Pierre et al., 2003). These effects could be costly if not adapted to: evidence from the UK suggests that total loss by the end of the century in milk production is valued at £13.4M in average years and £33.8M in extreme years (Fodor et al., 2018). The main adaptations identified in the literature are outlined below.

Genetic selection

Highly productive, specialised breeds are often unable to maintain their productivity in more extreme climatic or endemic disease situations (Hoving et al*.* 2014), so breeds with greater heat tolerance and general "hardiness" (also against cold stress from increased wind and wetter conditions) may be introduced as an adaptation (Renaudeau et al. 2012). There may be a resulting trade-off with production and efficiency as greater heat-tolerance tends to be correlated with lower productivity (Hoffmann, 2010), however cross-breeding with indigenous varieties may improve heat tolerance while maintaining productivity. In contrast, Hill and Wall (2017) observed that the feed conversion rate of higher genetic merit dairy cows which were selected for milk traits, were less affected by increasing thermal stress than non-selected cows (UK average). Therefore, identifying and selecting heat tolerant animals within productive breeds may be an viable approach. Gaughan et al. (2009) suggest either identifying phenotypes that will meet current and future market specifications within a heat-tolerant breed, or selecting heat-tolerant animals within breeds that currently meet market specifications. Certain traits, for example the naked neck and frizzle genes in poultry, have favourable effects on growth and laying performance (Fathi et al.2013; Zerjal et al 2013). Even coat colour can have an effect on the animal's ability to cope with heat (Tucker et al, 2008). Better utilisation of genetic diversity, improved thermal tolerance and robustness of animals, and optimal use of available natural resources in order to maintain productivity in a changing climate (Hoving et al. 2014), as well as breeding programmes that focus on attributes beyond productivity, including heat tolerance, will help the sector avoid productivity losses associated with heat stress.

Altering the environment the animal lives in

Altering the environment (either the housing or the physical conditions of where the animal is kept) the animal lives in is a potential adaptation to heat stress, although if nutrition, disease control and breeding factors are not optimal, this may not be effective (Renaudeau et al.2012). In hot climates, evidence shows that the productivity of housed animals is higher than non-housed dairy cows during periods of heat stress (Hill & Wall 2015). Beef animals have a higher upper critical temperature and are better able to cope with warmer conditions so it may not be necessary to house animals for as long as a lactating dairy cow. Housing is both an adaptation for those animals usually outside, who require increased shelter during periods of excessive heat or cold, and it is something that may itself require adapting in situations when it is the main environment for livestock. The construction of buildings or increased access to existing buildings, or the planting of shelterbelts will address both heat stress and cold stress from high winds and rainfall. During periods of housing animals will require concentrate feed and silage or fresh harvested forage and extra bedding.

Construction of buildings will require considerable capital expenditure, as well as the opportunity cost of the land. Cheaper alternatives include the planting of hedges and shelterbelts, providing shade and shelter for animals, which have the additional benefits of decreasing soil erosion, reducing the loss of nutrients to water, increasing biodiversity, reducing the risk of flooding, and sequestering carbon, although they will require some time after planting before they become effective. Shade provision is a simple and cost-effective method to minimise heat stress (Renaudeau et al. 2012; Brown-Brandl, 2005), and studies have demonstrated improved milk yield between shaded and non-shaded cows, depending on breed (e.g.Collier et al.1981 and 2006) and reduced mortality in feed-lot cattle (Bubsy and Loy 1996). Adjusting the stocking rate, particularly for intensively farmed animals can avoid the accumulation of radiant heat between animals and hence excessive heat stress (Burmeister et al 1986).

Improving the ventilation (either passive or mechanical) in buildings and in transportation vehicles is an important adaptation for heat stress in intensively farmed livestock (e.g. Yahav 2004, 2005, 2009, Struck et al. 2014). Other adaptations include improved house design and structures, the addition of cooling pads (Wang et al. 2014), fan systems, water sprays/misters to building as well as to animals directly, (summarised in Renaudeau et al. 2012) and/or outdoor areas (e.g., collecting yards) and/or transport vehicles (Turnpenny et al. 2001). The type of roofing can even play a significant role in the effectiveness of cooling animals and hence their productivity (Khongdee et al. 2010). Regulations and changes to building and transportation standards may need to be adjusted to account for a changed climate.

Adequate access to water (ideally chilled (Jeon et al.2006)) to aid thermoregulation is also crucial, and diets may need to be adjusted to maintain productivity during hot weather. This could include increasing the energy and nutrient density of the diet (Wang et al., 2010) to compensate for decreased feed intake during hot weather, supplementation with antioxidants (Chauhan et al. 2014), feed additives (Zimbelman et al., 2013), pharmaceutical additives (Liu et al., 2013) or herbal additives (Pan et al.2014). A low protein diet may also help maintain performance under periods of heat stress (Ghasemi et al 2014). Feeding strategies such as withholding feed during periods of heat stress have also shown to be effective, by preventing the metabolic peak and environment heat loads from occurring simultaneously in some species (e.g. poultry), whereas in others (e.g. cattle), feeding more frequently can increase daily consumption and avoid some of the negative effects of heat stress (Renaudeau et al. 2012). Health and disease implications of hot weather will also need to be managed as part of the adaptation.

Livestock may be transported at different ages and this is a factor that determines their vulnerability to thermal challenge in transit. Adult pigs, adult sheep, adult cattle (all for slaughter or for long distance export) and broiler chickens and turkeys at slaughter weight may be particularly susceptible to heat stress in transit whereas young animals (e.g. weaner pigs, piglets, calves, lambs and day old chicks) may be more affected by cold exposure and cold stress. In the case of extreme events or episodes, animals of all ages are detrimentally affected by both high and low temperatures. Most of the adaptations discussed previously will also be relevant when transporting animals, as well as improved vehicle design and operation, including mechanical ventilation, showering (cool water), misting systems or air conditioning and continuous provision of cool drinking water. Changes in loading or stocking density or space allowances per animal by producers/hauliers/drivers may be required, with the carriage of fewer animals per vehicle to reduce on-board heat and moisture production, and the re-scheduling of journeys to avoid the hottest periods of the day. This will require processing plant operations to be adjusted for slaughter animals. More broadly, the introduction of local slaughtering to avoid long journeys and the increased transport of carcases rather than live animals may be necessary – requiring a transformation in the current system (Park et al. 2012, Hadarits et al. 2017). Similarly, changing the locations of breeding hubs and increasing the number of such centres to provide breeding animals that are transported shorter distances may also be required. Changes in legislation (welfare) and regulation relating to transportation of animals may be necessary as temperatures increase (Moran et al. 2009).

Livestock may also experience cold stress through wetter and/or windier winters and springs. Many of the adaptations for heat stress will be the same types as for cold stress, such as providing shelter, housing animals, assessing regulations, and adjusting the timing of operations. Animals that are usually out-wintered may no longer be able to be, or for as long, requiring housing and associated management changes. Adaptations will necessarily vary between livestock types, with dairy cows having different requirements to beef cows and sheep, and pigs and poultry being different again.

Changing the timing of farm operations, particularly mating, transport, and shearing in sheep, is another mechanism for dealing with changes in conditions for livestock. While the decision to adjust the timing of shearing can be made relatively quickly, decisions regarding timing of mating are more difficult to make and changes would probably only be made after several successive changed seasons where the pattern of that change was similar. Once the decision has been made the farmer is then committed for that year, but depending on the nature and scale of the changes, may be able to revert back to a different date in the following year. Anecdotal evidence exists *(*Waterhouse, pers comm*)* that some farmers are changing the breeding dates of their stock in response to observed changes in seasons, while others are reluctant to change for social and traditional reasons. Farmers may be able to avoid young stock being exposed to adverse weather conditions, as well as match the supply of forage in changing seasons.

3.2.2 Variable precipitation and water availability

Demand management

One of the primary adaptation options in response to drought risk and water scarcity is managing the use of available water. This applies particularly to the use of irrigation water, and while irrigation is currently not commonly used in livestock systems in the UK, if the UK follows developments in other countries it may become more widespread in future. While irrigation can be an important adaptation to drought and used as a tool to smooth farmers' incomes (Foudi and Erdlenbruch 2012), it puts extra pressure on already scarce water supplies and can become maladaptive in certain contexts (Magnan et al., 2016). Demand management can come in the form of setting clear water use priorities between users as well as on-farm; increasing water-use efficiency; switching between irrigation technologies; (as well as improving the efficiency of irrigation systems (Frelih-Larsen et al*.* 2014), and examples of this are already being implemented in the UK (Rey et al. 2017).

Water collection and storage

Other adaptation options addressing drought and water scarcity centre on water collection and storage. These may include the construction of water storage capacity to capture rainwater and to store water collected or abstracted at times of high rainfall to be used during low rainfall periods.

Rainwater harvesting and storage may be in the form of smaller storage, such as tanks, to be used on a daily basis, as well as larger scale on-farm lagoons or reservoirs which would be used to provide water during periods of drought.

Soil management and improved drainage

Good farm and soil management practices will provide adaptation against drought and water scarcity as well as flooding. Options include shifting pasture from drought sensitive areas; soil management techniques to improve soil structure, field drainage and absorption capacity; and woodland planting (Wiltshire 2014; AEA Energy & Environment and Universidad de Politécnica de Madrid, 2007) which will also reduce the risk of run-off (Hjerp et al. 2012), and increase the soil carbon stocks, an ancillary benefit in addressing the causes of climate change. Soil management techniques for managing rainfall intensity include contour ploughing, increased drainage and the addition of organic matter into soils, all improving the absorption of water and minimising soil erosion.

Improved drainage has the dual benefit of improving the soil absorption capacity which can potentially increase yield in areas at risk of water shortage, retaining water in the case of shortage, as well as reducing waterlogging during periods of heavy rain. It does also have potential negative consequences of downstream flooding, a reduction in yield in areas prone to salinity issues, and possible water quality problems in streams.

Natural flood management

Strategies for adapting to the increased incidence in frequency and severity of flooding range from changes in soil management to natural flood management (NFM) techniques and hard defence structures. On-farm flood defences are likely to be less common as they require significant capital investment and are only likely to be adopted in the case of high-value land/production that is regularly threatened by a nearby river. However, NFM techniques such as the creation of or reversion to wetlands may be a more accessible option. Natural flood management refers to the enhancement or alteration and restoration of natural features and characteristics that could contribute to the management of flood risk, using techniques that work with natural processes, features and characteristics to manage the sources and pathways of flood waters. NFM measures broadly involve returning the environment to a more natural state, for example through re-meandering, restoration of disconnected floodplains, upland grip blocking, restoration of peatlands, restoration of native catchment woodlands, and the reinstatement of riparian woodlands and coastal realignment (McVittie et al. 2018; Jacobs Engineering 2011). NFM measures can also provide a range of ancillary benefits including improved water quality, restored habitats and increased biodiversity, and potential carbon sequestration. Generally however, NFM requires coordinated action and the farm-level benefits are limited if carried out in isolation from adjoining properties. Furthermore, many of the measures involve the conversion of current pastureland into non-productive land, at least for some of the time, such as wetlands or woodlands, which is likely to present a barrier to adoption, but emerging methods can help provide a comprehensive picture of the costs and benefits over time in an uncertain climate future (Dittrich et al. 2019). Research from the UK indicates that strategically placed, small scale planting of trees for shelter can be effective at improving the infiltration capacity of extensive areas of grazed permanent pasture (Caroll et al. 2004), providing additional benefits of shelter and shade for livestock as identified previously. However, the potential outcomes are very case and site specific and depend on a wide range of factors such as the amount of land used, the design and topography (Frontier Economics et al. 2013).

Drought tolerant pasture and feed varieties

Extensive research exists internationally, in regions much drier than the UK, such as Australia, New Zealand and Spain, to investigate species tolerant of low water availability (e.g. Marshall et al. 2016, Neal et al. 2009). In addition to drought tolerant species, there may be value in incorporating high feeding value forage species into pastoral systems, in order to counteract the drought effects by providing greater nutrition (e.g. Kemp et al. 2010). Incorporating legume and herb forage species has been shown to produce higher live weights than perennial ryegrass alone. Diversification of species in general, may improve the general resilience of the pasture system (Kirwan et al. 2007). Changing species is not always straightforward however and careful consideration should be given to growth patterns and production trade-offs (Lee et al. 2013).

Planning

Developing contingency plans in the event of a flood, or when a flood appears to be likely, is crucial to ensure the safety of livestock as well as people on the farm. Being prepared for where and when to move stock and how, is critical for areas likely to experience flooding either now or in the future. Building resilience is generally seen as an important flood management strategy, so that systems can return to 'normal' as quickly as possible after a flooding event.

Shelter and feed

Providing adequate shelter for animals during a flood is important to reduce the risk of mortality, and ensuring sufficient feed supplies are available when animals are unable to graze on pasture.

Insurance

Insurance is a contested adaptation measure as it transfers rather than reduces risk, and potentially disincentivises farmers from taking adaptive measures to reduce risk (Linnerooth-Bayer and Hochrainer-Stigler 2014). Foudi and Erdlenbruch (2012) find a direct and significant link between yield insurance and irrigation adoption – having opted for yield insurance significantly decreased the probability of adopting irrigation. In the short term however insurance remains an important tool for farmers to protect their livelihoods from climate variability, by pooling risks across communities and regions. Insurance instruments can provide incentives for adaptation by using reduced premiums to reward investment in risk reduction activities (Linnerooth-Bayer & Hochrainer-Stigler 2014), and perhaps to discourage maladaptive adaptation actions (as increased irrigation can be in times of water scarcity). On the negative side, insurance can be too costly for small- scale farmers or those on low incomes, and insurers are often reluctant to cover catastrophic events, which may require the introduction of publicly backed insurance. Innovative alternatives to traditional insurance programmes are increasing, including index-based micro-insurance programmes, where limited cover is offered to low-income markets where products are written against physical or economic triggers rather than the loss itself (Hochrainer-Stigler & Pflug 2012, Barnett and Mahul 2007). Other alternatives include national insurance programmes, to cover high risk-level droughts, floods and other hazards where private insurers are reluctant to provide cover.

Market based solutions: Water charging/tradeable permits

At the policy level, market-based solutions, such as water charging or tradeable permits may achieve more efficient water use, although the evidence on their effectiveness is mixed (Garrido and Calatrava 2010; Cornish et al.2004).

3.2.3 Increased risk of agricultural pests and diseases

Livestock management

At the farm level, the main tool available to address the increased risk of pests and diseases is livestock management. Livestock management drives the contact processes between hosts (livestock and wildlife) and parasites whether through rates of population mixing (*i.e.* risk of direct transmission) or rates of contact with environmental distributions of parasites and pathogens *i.e.* risk of indirect transmission). Stocking density and grazing management practices are therefore essential to combat livestock disease.

Vaccination is an adaptation option, and the use of thermostats and rapid-cooling to reduce pest and disease infestation where appropriate. Parasite prevalence and diversity is closely correlated with stocking density (Altizer *et al.*, 2003; Côté *et al.* 1995; Gillespie *et al.*, 2005). This is due, in part, to the impact of host density and ensuing levels of social contact on parasite transmission; with the frequency of contact between infected and uninfected individuals increasing as group size increases. As well as increasing contact between livestock, diminishing resources (*e.g.* water in summer) may result in the crowding of livestock with infective wildlife, increasing interspecies transmission potential. As the suitable climates for wildlife shift, the levels of contact between wildlife and livestock will change. Similarly, adaptations in response to other climate stressors may exacerbate the disease-risk, for example conserved forage can often be contaminated with wildlife excreta that represent a risk of infection (Daniels et al. 2003), and the enforced confinement of animals (perhaps during extreme rainfall/flooding for example) will increase the contact between animals and potentially the transmission of airborne pathogens (Moran et al. 2009). Likewise, the stress associated with high stocking rates in these situations may also affect animal health. Extended livestock grazing seasons may result in increased exposure to environmental distributions of parasites and pathogens.

Livestock disease epidemiology is highly sensitive to host community composition and particularly population mixing (*e.g.* livestock movement through trade). Any change in epidemiological variables is likely to have knock-on consequences affecting the risk profile of parasites and pathogens transmitted via direct contact. At the policy level, increased surveillance of pests and diseases is likely to be a cost-effective adaptation strategy (Moran *et al.* 2013), and essential to ensure the health of livestock at the regional scale.

Pests and diseases may also affect the production of forage and fodder for livestock. The use of pest-resistant varieties, natural predators, and monitoring of pests and disease patterns to prevent loss may be necessary (Goldson et al. 2016). A sustainable integrated crop protection strategy, as well as an advisory service to farmers are also potential adaptations.

3.2.4 Pasture area changes due to changes in optimal farming conditions and changes in forage quantity and quality.

Changes in precipitation, increased temperatures in critical periods; increased erosion; and a loss of soil water retention capacity may have implications for the area suitable for pasture and grazing. Adaptations in response to this can focus initially around pasture management changes which have been discussed in earlier sections, or as the changes become more pronounced, consider alternative land uses.

Climate change may affect the species composition of the sward (Rose et al, 2016), have negative impacts on the quality (AbdElgawad et al, 2014; Lee et al, 2017; Dellar et al, 2018) and variable impacts on the quantity of fodder production (Brown et al, 2017). Changing precipitation patterns, increased temperatures and elevated CO_2 levels will all influence plant growth (Chang et al, 2015; Dellar et al, 2018; Qi et al. 2018). A prolonged grazing season may be beneficial for perennial vegetation such as grassland, providing other climatic effects such as drought or flood are not also experienced (Brown et al, 2017). In response to changes in forage quantity and the loss of quality resulting from a changing climate, there is again a range of potential adaptation options. Changing the balance of grazing and cutting grass and changes to the grazing regime are both management adaptations that may help minimise this impact. Increased use of forage legumes may help provide resilience, although the effect is variable (Bloch, 2015; Hofer et al, 2016; Klaus et al, 2016; Carlsson et al, 2017) and moderated by rates of fertiliser applications and the availability of soil N (Hofer et al, 2016; Hofer et al, 2017). Changing the seed mix to include a range of complementary species and cultivars will enhance the productivity of the sward under a variable climate (Mäkinen et al., 2015). However, the options are limited compared to arable crops (Olesen et al., 2011), which is partly due to the age of the grassland swards. Changing the timing of operations to minimise the impact on forage production may be necessary, and adjusting the stocking rate to suit the new conditions is also an adaptation to consider.

Feed storage provides a certain amount of resilience as surplus feed produced during good years can be stored for years where climate impacts effect forage production and quality. Fodder storage is an important adaptation in developing countries (e.g. Chatterjee et al. 2005), although successive droughts would limit the success of this as an adaptation. Regional climate forecasts may be able to provide farmers with better information on the likely climate outlook for their area year by year. Fodder will deteriorate over time, and again in developing countries farmers are returning to traditional methods of preservation (Chatterjee et al. 2005), which may provide insights for UK farmers. Import of feed may be a necessary adaptation when storage is not sufficient, but may be costly and relies on there being surpluses elsewhere.

4. Adaptation Costs

The adaptations identified in the previous section vary significantly in terms of their likely costs: from actions that can be employed relatively simply and at low- or no-cost, to those that would require large investments of capital or labour. Many of these adaptations may not incur any financial costs at all. In this section, we group the different adaptation options according to the type of cost they might incur. We break down costs into:

- *No financial cost*: these adaptations would not incur any financial cost, only changes in management practice and behaviour.
- *Capital cost*: these adaptations would incur a one-off capital cost.
- *Operational cost*: these adaptations would incur ongoing operational costs, which would include maintenance as well as labour costs.

- *Opportunity cost*: these adaptations would involve an opportunity cost[1] in terms of the lost opportunity arising as a result of adopting the adaptation.
- *Productivity cost*: these adaptations may result in a loss in productivity.
- *Ancillary financial benefit*: these adaptations would result in a financial benefit beyond the avoided climate impact, also known as an ancillary benefit, or a win-win.

Each adaptation may potentially incur more than one type of cost, depending on the situation. We have considered all potential costs for each adaptation (based on expert judgement); each adaptation may not necessarily fall into all of the categories indicated as being potential costs – it will depend on the specific circumstances surrounding that particular adaptation action in an individual situation. Table 2 summarises all the adaptations discussed in the previous section and provides an assessment of the types of costs they would incur.

This grouping by type of cost highlights some important points for decision-makers. The first is that many of the potential adaptations can be adopted at no cost, and some even have the potential to provide a financial benefit beyond the climate change adaptation benefit. Most of these benefits occur through improvements in efficiency, such as water conservation and efficiency measures, and improving soil fertility. As such, these types of benefits would be considered best-practice and could be implemented regardless of climate change (also referred to as "no-regrets"). Many of the adaptations judged to incur no cost involve changes in the timing of operations or changing cultivation practices. Some of the practices included under no-cost then list other costs, including capital or operational costs as well, which may appear contradictory, however as mentioned above, the costs listed are simply the potential costs and the reality will be different in different circumstances.

[11] While technically there is an opportunity cost to everything, and for any farm management option, the opportunity cost is the value of the next-highest-valued alternative to use of that resource, in this context we use opportunity cost to refer to the lost opportunity to use the land

Furthermore, some of the adaptations identified constitute a broad category of adaptations, such as "increase rainfall interception capacity", under which a range of measures may fall, some of which will not incur any cost and others may incur a capital and/or operational cost.

The largest group of costs fall under the heading of operational costs, which include both maintenance as well as labour costs. Most of the adaptations here would in fact incur labour costs, involved for example with moving animals in response to weather or pasture conditions, planting and maintaining trees or plants for shelter or water absorption, and monitoring animals for disease etc. Maintenance costs are associated with some of the 'hard' adaptations such as flood defences, those that involve planting trees or creating wetland areas, and any that involve machinery or technology such as irrigation and some precision agriculture techniques that will require on-going maintenance.

Capital costs are arguably the type of cost most likely to pose a barrier. Clearly, the greater the upfront cost, the more of a barrier it will pose, although in many cases the capital cost would not be large, such as changing the seed mixture (may not incur any capital cost depending on the change). Some of the adaptations again include a range of possibilities, such as increasing the rainfall collection capacity, which could range from the installation of a simple tank, to the construction of an on-farm reservoir. Other adaptations would require a more significant capital outlay, notably the construction of hard flood defences and housing for animals. Decisions involving a large capital investment will often involve particular attention through economic analysis (Dittrich et al. 2017).

The final groups of costs involve opportunity and productivity costs. The opportunity costs primarily relate to the loss of productive land through a change in land-use, such as through the planting of trees or reservoir creation, or the removal of land (at least some of the time) from production for the purposes of flood defence. It could be argued that the land may be lost due to flooding in the absence of the adaptation in any case, however this would not always be so and in some cases, the area of land removed from production may be significant. The use of land for natural flood management is usually managed at a public level; a range of mechanisms to compensate land-owners exist, from outright purchase of the land to annual payments in return for NFM services (Beedell et al. 2011).

Productivity costs refer primarily to the trade-offs that may occur when selecting for more climate-resilient breeds of animals or strains of pasture/crops, however the productivity loss may not occur in every case, and over time as the new breed/varieties become more utilised, research and breeding is likely to recover the initial lost productivity. Other productivity costs such as a reduced stocking rate may be more difficult to recover from, but the aim would be for the benefits in terms of animal health and mortality to outweigh the lost production.

Table 2: Summary of adaptation options together with assessment of cost type (no financial cost; benefit (positive financial outcome); capital cost; operational cost; opportunity cost and productivity cost). Shading identifies the applicability of a column to the adaptation in that row.

		Type of cost/benefit					
Climate impact	**Adaptation option**	No financial cost	Benefit (positive financial outcome)	Capital	Operational (incl.maintenance, labour etc)	Opportunity	Productivity
Heat Stress	Genetic selection						
	Housing animals: constructing new sheds						
	Housing animals: moving animals into existing buildings						
	Increase shelter & shade for animals						
	Addition of cooling pads, ventilation, water sprays/misters to building and/or outdoor areas, and/or transport vehicles						
	Ensure adequate access to water (indoors and outdoors) to aid thermoregulation						
	Diet management						
	Manage health and disease implications of hot weather (e.g., fly strike, acidosis increases during heat stress)						
	Adjust stocking density						
	Changes in slaughtering systems						
	Changes in transport regulations						
	Change timing of operations						
variable precipitation and water	Irrigation						
	Set clear water use priorities						
	Increase water use efficiency						

	Change irrigation technology						
	Technical improvements in irrigation equipment, efficiency, and ability to collect rainwater						
	Insurance						
	Increase rainfall collection capacity, including reservoir installation						
	Shift pasture from drought-sensitive areas						
	Introduce drought-tolerant crops						
	Improve field drainage and absorption capacity						
	Reduce run-off through contoured hedgerows and buffers						
	Woodland planting						
	Use of precision agriculture techniques						
	Market based solutions including water charging/tradeable permits						
	Hard defences						
	Natural flood management (incl. restoration of woodlands and peatlands, riparian planting, remeandering of rivers)						
	Contour ploughing						
	Addition of organic matter into soils						
	Resilience planning						
Increased risk of pests and diseases	Livestock management including reduced stocking rate						
	Vaccination						
	Use of thermostats and rapid-cooling to reduce pest and disease infestation						
	Use of pest-resistant varieties						
	Increased monitoring and surveillance for disease						
	Develop sustainable integrated pesticides strategy						
	Use of natural predators						
Changes in pasture area and forage quality and quantity	Improving soil fertility						
	Confinement feeding						
	Higher lucerne proportion						
	Changing cultivation practice						
	Alternative crops/pasture						
	Balance of grazing and cutting						

	Increased use of legumes						
	Feed storage						
	Feed import						
	Supplemental feeding						

5. Discussion and conclusion

Despite many adaptations being either low-cost or even generating financial benefits beyond the climate resilience, still relatively little implementation of climate change adaptation exists (exceptions exist, for example in water management (Rey et al., 2017)). Although farmers are adaptive and respond to a multitude of drivers as they manage their businesses, numerous barriers to the adoption of adaptations do exist. These have a multitude of origins and a detailed discussion of these is beyond the scope of this paper (see for e.g. Carlton et al. 2015; Niles et al. 2016; Niles et al. 2015; Prokopy et al. 2015; Wreford et al. 2017), but a focus on current and observed changes in the weather and climate may be more likely to trigger action and overcome barriers than future, more hypothetical, changes. Many agricultural practices do not require a long lead time and may also be reversible, so the challenges that climate uncertainty poses to other sectors (Dittrich et al. 2017; Hallegatte et al. 2012) are not as great in agriculture. It is also important however, that farmers are attuned to the changes that may occur over the longer term, and consider these when making more significant changes, such as expansion or breed selection.

Figure 1 provides a conceptual framework identifying the ways in which the different time frames can be addressed in adaptation planning in the present. On the left, adaptation options to current impacts are the most straightforward, with little uncertainty, where the farmer is able to recognise a changing situation and identify appropriate adaptation strategies, either through their own knowledge and experience or by information provided through networks. However, to ensure future resilience, the farmer should also begin thinking about the impacts that may not be currently observed (or without sufficient regularity to convince the farmer that the shift is permanent), but are likely to occur within the next few years. The farmer can begin to accomodate these likely changes by considering them at decision-making points in their business cycle. For example, when routinely replacing existing buildings, the farmer could incorporate features that may make the building more suitable in a future climate (for example with more ventilation). Similarly, if the farmer was reviewing their land-use plan or considering expansion, informing themselves about the likely climate impacts in the next few years would be prudent. Finally, for the climate changes that are not likely to occur until further into the future, there is less that individual farmers are likely to do, as the primary role lies with the government and research bodies into research and information sharing (Wreford et al. 2010). This article has focused on incremental adaptations to maintain current systems, but it is possible that changes in the UK's climate in future mean that more transformative changes will be required into different types of systems and processes (Park, 2012; Wise et al., 2014), including taking advantage of any opportunities that changes present.

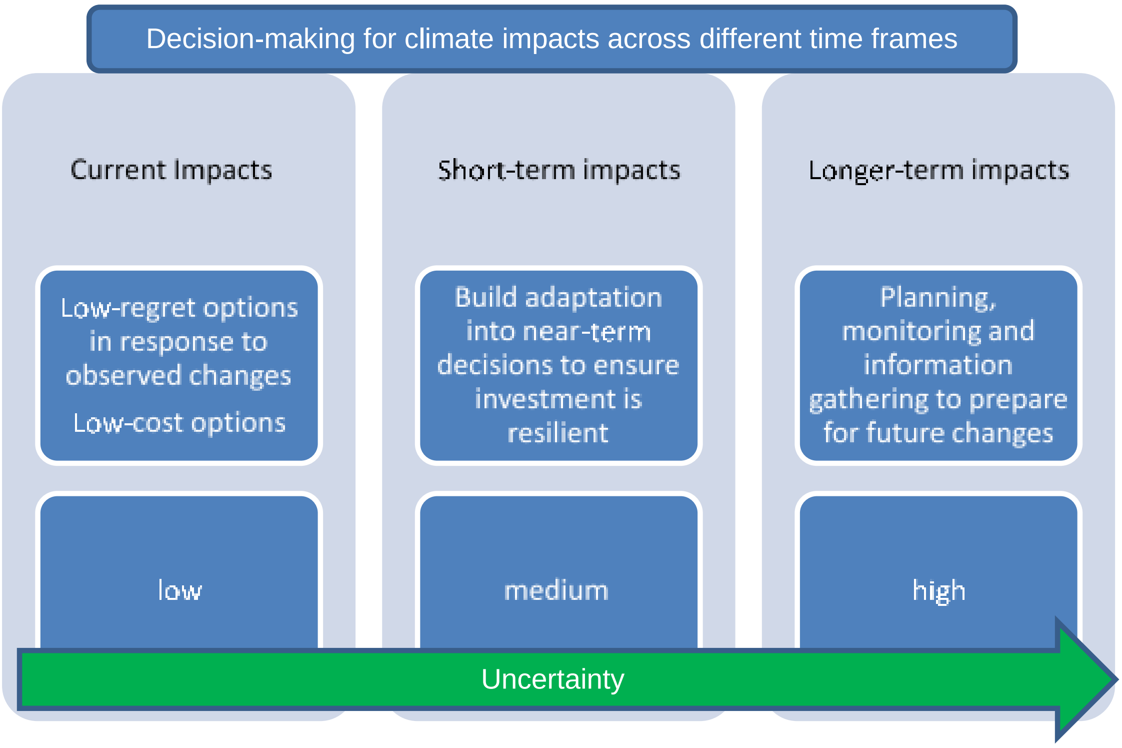

Figure 1 Decision-making for climate impacts across different time frames (adapted from Watkiss 2016).

This article has summarised the main climate projections for the UK and their associated impacts for livestock production. We have identified a wide range of options available for adaptation to these, and assessed them based on the types of costs they incur. Many options do not involve a financial cost to the farmer, and may even generate a financial benefit over and above the avoided climate damage. Understanding what the options are, and the types of costs they may incur, is an important first step when considering how to adapt. These options form part of a bigger picture of adaptation that is beyond the scope of this article. The focus has been on the UK, but the approach, as well as many of the adpatations, can be applied in other areas.

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